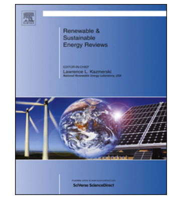
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Photovoltaic technology selection: A fuzzy MCDM approach

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ABSTRACT

This paper focuses on standards battles for photovoltaic technological systems. Five photovoltaic technologies are currently commercially available and it is still unclear which of these technologies will emerge as the dominant design. Based on the literature and on expert interviews, we develop and analyze categories and factors for technology dominance for these systems. By applying the analytic hierarchy process, we determine the importance of these factors and the chances of one of these five technologies becoming the dominant photovoltaic technology. The crisp and fuzzy (logarithmic fuzzy preference programming) analytic hierarchy process method is used to analyze the data. The results show that the standard support strategy is the most important category, and that pricing strategy and technological superiority are the most influential factors in the dominance process. Furthermore, the first generation technology mono-crystalline silicon photovoltaic has the best chance of achieving dominance (30% chance). The results of this study are useful for multiple stakeholders (e.g. energy policy makers and photovoltaic module companies) who have to make the decision as to which standard should be supported for photovoltaic technology.

Contents

1. Introduction

The unlimited availability of sunlight and the ability of photovoltaic (PV) cells to directly convert this radiation into electricity have made PV a promising renewable energy technology. Since the invention of the first efficient[1] photovoltaic cell during the 1950s, this technology has received considerable attention from both the scientific world and from governments. The oil crises during the 1970s and the subsequent rising oil prices led to incentives for PV R&D and market introduction. Currently, five PV technological designs are commercially produced. These designs are currently fighting for market dominance in what economics and management researchers refer to as "standards battles" or "platform wars" [1]. For every involved actor, it is crucial to understand which design has the best chance to achieve dominance: for firms, it is important which design they should support in their products and for consumers, it is important to invest in products that have implemented the design that wins the battle (and thus become the dominant standard); "otherwise they may face problems related to interoperability with other products and/or may lack future support for their products" [2].

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[1] These first cells had an efficiency of about 4%.

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Several scholars have attempted to explain the outcome of these technological competitions [1,3–5] and offer frameworks of factors for standard dominance. However, what is very important here, which has unfortunately been neglected in the literature, is to understand the relative importance of different factors. Undoubtedly, ranking the technologies in order to find the most dominant technology is not possible if decision/policy-makers don′t have knowledge about the relative importance of the determinant factors for standard dominance. We aim to close this gap in the literature by developing a framework for standard dominance for photovoltaic technological systems and assigning weights to the factors for standard dominance. The overall objective is to explore whether the framework can be used to explain the outcome of technology standards battles for photovoltaic technological systems and which technological design will have the highest chance of achieving dominance. This work adds to the growing body of literature focusing on dominant designs and standardization [3,4,6].

We begin by reviewing the literature on factors for standard dominance in Section 2. Subsequently, in Section 3, we provide an overview of the photovoltaic industry. Next, in Section 4, we discuss our methodology. The results are presented in Section 5. We conclude in Section 6.

2. Theory

Many scholars from various disciplines have attempted to explain the outcome of standards battles [1,3–5]. Network economists [7–9] focus on market mechanisms that indirectly affect standard dominance. Examples of market mechanisms are the existence of network and learning effects whereby technologies increase in value the more they get adopted. Under the influence of network effects and learning effects, the installed base of users (e.g. the number of adopters of the technology) partly influences the outcome of standards battles [3,10]. Thus, it is pivotal to try to positively influence this installed base of users.

Technology management scholars have proposed various firm level factors that positively affect the installed base. Standards that are *technologically superior* compared to competing standards have an advantage and more users will choose to adopt these standards leading to an increase in installed base [11]. However, a standard that is technically superior does not always achieve dominance in the market [12]. Installed base can also be increased through the *timing of entry* strategy pursued by the standard supporter. By entering the market earlier than competitors, firms may *pre-empt the scarce assets* in the market (such as important manufacturers of complementary goods) [13]. However, for this strategy to work firms need to have the possibility to choose their timing of entry and therefore firms need sufficient *financial resources* [14]. These resources can also be used for *marketing communications* through for example, pre-announcements [1]. Furthermore, these resources are essential if a firm chooses to follow a penetration *pricing strategy* [9] whereby a product in which a standard is implemented is priced low in order to encourage potential users to adopt the product, thereby increasing the standard′s installed base. Other important factors mentioned in the literature include *operational supremacy* through for example, the possession of a "superior production capacity" [6], and *reputation and credibility* as past success in establishing dominance with standards positively influences the expectation with regard to new standards [15]. A firm′s *appropriability strategy* can also influence standard adoption. For a standard, a firm may apply an open licensing policy. As a result, competitors may copy the standard which will increase its chances of achieving dominance [5,16]. Van den Ende et al. [17] studied three historic standards battles and found that the *diversity in the network* of actors involved in the standard and the *flexibility of the standard* (or the extent to which the standard is changed to changing user requirements) are important reinforcing factors affecting standard dominance. Some scholars emphasize the importance of *commitment.* For a standard to achieve market dominance, each actor involved should sufficiently support the standard [5,18]. Additionally, Schilling [3] emphasized the importance of *learning orientation* or the extent to which the group of standard supporters learns from experiences in prior standards battles.

Some authors have proposed various frameworks for standard dominance integrating firm level factors and market mechanisms [3–5]. Other scholars have focused on factors that affect the likelihood and speed of standard dominance. For example, Brown and Hendry [19] describe how public demonstration projects and field trials accelerate the implementation rate of photovoltaics. However, in most studies, the focus lies on a selection of the total list of possible factors for standard dominance [3,5,6]. In this study, we take a more comprehensive approach. Recently, Van de Kaa et al. [5] conducted an extensive literature study resulting in a framework for format dominance[2] consisting of five categories and 29 factors. The categories are characteristics of the standard supporter, characteristics of the standard, standard support strategy, other stakeholders, and market characteristics. In this paper, we build on van de Kaa et al.′s framework and focus on the first four categories since the factors underlying these categories can be directly affected by the stakeholders involved in standards battles. Market characteristics, on the other hand, are given and their value does not differ for alternative standards in a standards battle.

3. Photovoltaic industry

Every year the earth receives enough energy from the sun to cover for the world′s energy needs, especially in the amount of electricity needed. In 2009, 0.0048 PW[3] was used for global electricity production, while the earth received 174 PW from the sun [20,21]. While almost all forms of energy on earth indirectly originate from the sun′s power, photovoltaic (PV) technologies have the potential of directly converting the sun′s radiation into electricity.

At present, five PV technologies are commercially available. These technologies are subdivided into two generations. The first generation technologies are multi-crystalline silicon (mc-Si), invented in 1951, and mono-crystalline silicon (sc-Si), invented in 1954. The second generation technologies are cadmium telluride (CdTe), invented in 1972, CuIn(Ga)Se2, copper indium (gallium) selenide (CI(G)S) invented in 1975, and amorphous silicon (a-Si), invented in 1976. Typical conversion efficiencies of first generation technologies are currently 15% to 20%, whereas those of second generation technologies are currently 7% to 15% [22]. Third generation technologies are currently being developed but are not available on a commercial basis and are therefore not included in this research.

Although PV technologies only have a 5.1% market share in electricity production from renewable energy technologies, growth rates are significant with 72% in 2010 and 74% in 2011 [23]. The top five countries in terms of total installed capacity[4] in 2011 were Germany (24.8 GW), Italy (12.8 GW), Japan (4.9 GW), Spain (4.5 GW) and the USA (4.0 GW) [23].

In 2011, the aggregate size of the global PV industry exceeded 100 billion USD. Competition is fierce. Between 2000 and 2011,

[2] In Van de Kaa et al. [5] standards are referred to as formats. We will use the term standards throughout this paper.

[3] Petawatts, 10^{15} W.

[4] Installed capacity here refers to the total amount of electricity generation capacity from PV technology that is installed in a specific country. It is expressed in Gigawatt (GW), 10^{9} W.

leadership in PV production shifted from the USA to Japan to Europe to Asia [23]. In 2011, the top three companies with the largest market shares in PV modules worldwide were Suntech Power (China: 5.8%), First Solar (USA: 5.7%) and Yingli Green Energy (China: 4.8%). As the PV industry is characterized by increasing returns through strong learning effects see e.g. [24] one would thus expect a dominant design to emerge. However, since no technology has more than a 50% market share [25], there is currently no dominant PV technology. In 2011, the first generation PV captured about 80% of the market and second generation about 20% [23].

4. Methodology

4.1. The analytic hierarchy process (AHP)

The choice for a PV technology is a multiple criteria decision-making (MCDM) problem. The criteria which are often conflicting need to be compared on different scales. Multiple factors are found to influence the PV dominance process using incommensurable scales, together with several (though finite) competing PV designs from which the best needs to be selected by firms, which makes this a multi-criteria decision-making situation. The AHP, as a robust MCDM method, proposed by Saaty [26,27] is used to compare factors and technological designs and to structure this decision-making situation.

Because the AHP method uses simple scoring questions and a schematic overview of the factors, it is very useful in situations with respondents who are not familiar with the underlying theoretical concepts of the decision-making situation. The AHP method has successfully been used in numerous applications, for example, in forecasting, evaluation and prioritizing studies. An overview of recent applications is given in Sipahi and Timor [28] and Vaidya and Kumar [29]. The methodology of the AHP consists of the following steps (a detailed explanation can be found in Saaty and Vargas [30]).

Structuring the decision-making problem as a hierarchy, with an overall goal, criteria, sub-criteria and alternatives.

Constructing a set of pairwise comparison matrices by experts on all elements of the hierarchy, using the ratings from Table 1.

Applying some simple calculations to obtain the final relative weights of the criteria and decision alternatives, based on which the alternatives are ranked.

4.2. Criticism of the crisp AHP

Over the years, several researchers have criticized the AHP method [31–36]. The major shortcomings are the possibility of rank reversal and the tolerance for inconsistent judgments. To overcome these problems, multiple methods have been proposed [33]. In this research, we use the Logarithmic Fuzzy Preference Programming (LFPP) method as described by Wang and Chin [37] since it is a robust method based on previous methodologies. The main difference between crisp and fuzzy AHP (FAHP) is that FAHP, uses linguistic variables instead of crisp numbers to provide the pairwise comparisons. This makes FAHP closer to the real way of human thinking, judging and reasoning (see Table 1 and Fig. 1 [38]).

4.3. The logarithmic fuzzy preference programming method

The LFPP method proposed by Mikhailov [39] makes use of triangular fuzzy numbers (see Fig. 1). Moreover, this approach follows as a substitute to earlier work on deriving weights from fuzzy comparison matrices, e.g., from Chang [40] and Van Laarhoven and Pedrycz [41]. According to Wang and Chin [37], the LFPP method can be used to overcome the shortcoming of finding incorrect weights or problems with multiple optimal solutions from earlier versions of the fuzzy AHP method (e.g. [41]).

The first steps of the LFPP analysis are similar to the crisp AHP method, though with the analysis of the questionnaire, the fuzzy (triangular) qualification of judgments is introduced according to the ranking as shown in Table 1 and Fig. 1. The operational laws of fuzzy numbers $\tilde{N}_1 = (l_1, m_1, u_1)$ and $\tilde{N}_2 = (l_2, m_2, u_2)$ are, with all l, m, u being$\{\in \mathbb{R} | > 0\}$:

$$\text{Fuzzy addition} \oplus: \quad \tilde{N}_1 \oplus \tilde{N}_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{1}$$

$$\text{Fuzzy multiplication} \otimes: \quad \tilde{N}_1 \otimes \tilde{N}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \cong (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \tag{2}$$

$$\text{Fuzzy division} \oslash: \quad \tilde{N}_1 \oslash \tilde{N}_2 = (l_1, m_1, u_1) \oslash (l_2, m_2, u_2) \cong \left(\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{u_1}{l_2}\right) \tag{3}$$

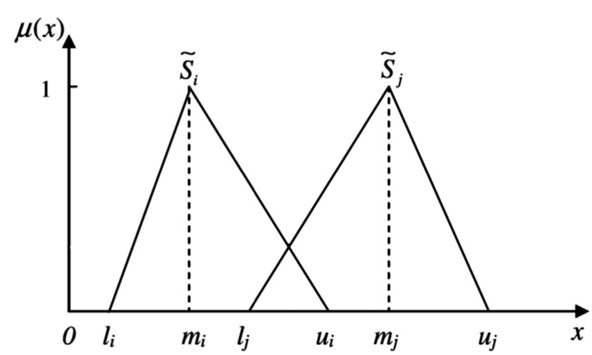


Fig. 1. Representation of two TFNs, $\tilde{S}_i = (l_i, m_i, u_i)$ and $\tilde{S}_j = (l_j, m_j u_j)$.

Table 1
AHP and FAHP numbers used for comparison.

Crisp numbers (Saaty [26,27])	Triangular fuzzy numbers (TFN) {*l*, *m*, *u*}	Description
9	{8, 9, 9}	Extreme importance or preference
7	{6, 7, 8}	Very strong or demonstrated importance or preference
5	{4, 5, 6}	Strong or essential importance or preference
3	{2, 3, 4}	Moderate importance or preference of one over another
1	{1, 1, 1}	Equal importance or preference
2	{1, 2, 3}	Intermediate values
4	{3, 4, 5}	
6	{5, 6, 7}	
8	{7, 8, 9}	
x^{-1}	$\{u^{-1}, m^{-1}, l^{-1}\}$	Reciprocal number (for symmetric pairwise comparison matrix)

The subsequent steps of the LFPP method [37]:

The pairwise comparisons are organized in a square matrix. Mathematically, the fuzzy judgement matrix $\tilde{A}$ is given by (with column j and row $i=1,\ldots,n$):

$$\tilde{A}=\begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array}\begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \left[\begin{array}{cccc} (1,1,1) & \tilde{a}_{12} & & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & & \tilde{a}_{2n} \\ & & \ddots & \tilde{a}_{in} \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \tilde{a}_{nj} & (1,1,1) \end{array}\right] \end{array},$$

$$\text{with } \tilde{a}_{ij}=\{l_{ij},m_{ij},u_{ij}\} \text{ and } 0<l_{ij}\le m_{ij}\le u_{ij} \tag{4}$$

Because $\ln\tilde{A}_{ij}\approx\{\ln l_{ij},\ \ln m_{ij},\ \ln u_{ij}\}$, the original pairwise continuous membership function:

$$u_{\tilde{N}}(x)=\begin{cases}\frac{x-a}{b-a}, & a\le x\le b\\ \frac{c-x}{c-b}, & b\le x\le c\\ 0, & \text{otherwise}\end{cases} \tag{5}$$

Can be rewritten as:

$$u_{ij}\left(\ln\frac{w_i}{w_j}\right)=\begin{cases}\frac{\ln\frac{w_i}{w_j}-\ln l_{ij}}{\ln m_{ij}-\ln l_{ij}}, & \ln\frac{w_i}{w_j}\le\ln m_{ij}\\ \frac{\ln u_{ij}-\ln\frac{w_i}{w_j}}{\ln u_{ij}-\ln m_{ij}}, & \ln\frac{w_i}{w_j}\le\ln m_{ij}\end{cases} \tag{6}$$

Now, to determine a crisp priority vector (similar functionality to the crisp AHP method), first the previously mentioned membership degree needs to be maximized:

$$\max\lambda=\min\left\{\mu_{ij}\ln\frac{w_i}{w_j}\right\},\text{with } i=1,\ldots,n-1;j=i+1,\ldots,n \tag{7}$$

This can be rewritten to the following model:

$$\text{Maximize}\quad 1-\lambda \tag{8}$$

$$\text{Subject to}\begin{cases}\ln w_i-\ln w_j-\lambda\ln\frac{m_{ij}}{l_{ij}}\ge\ln l_{ij}, & i=1,\ldots,n-1;j=i+1,\ldots,n\\ -\ln w_i+\ln w_j-\lambda\ln\frac{u_{ij}}{m_{ij}}\ge-\ln u_{ij}, & i=1,\ldots,n-1;j=i+1,\ldots,n\\ w_i\ge 0, & i=1,\ldots,n\end{cases}$$

However, when solving formula (8), the value λ may become negative, because not all weights will be able to meet all the judgments in the fuzzy comparison matrix $\tilde{A}_{ij}$.To overcome this problem, the nonnegative values δ_{ij} and η_{ij} are introduced. This results in the following model:

$$\text{Minimize}\quad J=(1-\lambda)^2+M\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}(\delta_{ij}^2+\eta_{ij}^2) \tag{9}$$

$$\text{Subject to}\begin{cases}x_i-x_j-\lambda\ln\frac{m_{ij}}{l_{ij}}+\delta_{ij}\ge\ln l_{ij}, & i=1,\ldots,n-1;j=i+1,\ldots,n\\ -x_i+x_j-\lambda\ln\frac{u_{ij}}{m_{ij}}+\eta_{ij}\ge-\ln u_{ij}, & i=1,\ldots,n-1;j=i+1,\ldots,n\\ \lambda,x_i\ge 0, & i=1,\ldots,n\\ \delta_{ij},\ \eta_{ij}\ge 0, & i=1,\ldots,n-1;j=i+1,\ldots,n\end{cases}$$

From formula (9), the values of x can be found, which represent the weights of the alternatives: $x_i=\ln w_i$ for $i=1,\ldots,n$. Big M is a specified constant (>1000) which is introduced to find weights within the supported intervals of the judgment and to minimize violations.

After finding the optimal solution, the weights w_i are normalised by:

$$w_i^*=\frac{e^{w_i^*}}{\sum_{j=1}^{n}e^{w_j^*}},\ i=1,\ldots,n \tag{10}$$

If $\lambda^*>0$, the criteria match the priorities, also the larger the value of λ^*, the higher the consistency. If $\lambda^*=0$, the possibility of inconsistencies can be checked by calculating δ^*:

$$\delta^*=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}(\delta_{ij}^2+\eta_{ij}^2) \tag{11}$$

when $\delta^*\ne 0$, there are inconsistencies in the fuzzy judgments, similar to the crisp AHP method; the larger δ^*, the higher the inconsistency. Wang and Chin [37] do not describe a threshold like Saaty [27] at which the comparisons are inconsistent and should be rechecked. However, in one example they calculate a value of $\lambda^*=0$ and $\delta^*=0.2271$ and consider this as “strong inconsistency”.

With fuzzy numbers in the comparison matrices inevitably some form of inconsistency is introduced [42] even if the matrices are found to be consistent using the Consistency Ratio (CR) from the crisp AHP analysis. This is a shortcoming of the fuzzy AHP method in general. These inconsistencies come from the possible overlap that fuzzy numbers have, illustrated by the grey area in Fig. 2.

4.4. Data collection

This research uses a two-stage process to explore the importance of factors for standard dominance for PV technology and to determine which technological design will have the highest chance of achieving dominance. During the first stage, we constructed a list of factors that influence the technology selection process, by using an existing framework in the literature [5], and we conducted three expert interviews to determine which factors are relevant for the PV market.

In the second stage, we used the analytic hierarchy process to structure a questionnaire to analyze the importance of factors in the decision-making process of firms in the PV value chain and used both the crisp and the fuzzy AHP method to determine the relative importance of these factors. We conducted six semi-structured interviews to ensure mutual understanding and checked the completeness of the list of factors with the experts during each interview.

We interviewed nine Dutch industry experts from four different sectors. We selected two experts from universities for their fundamental understanding of PV technologies and the latest technological developments. We chose three experts from PV manufacturers for their knowledge of the PV market, three experts from semi-public research institutes for their overview of both the latest technological advances and their knowledge of market

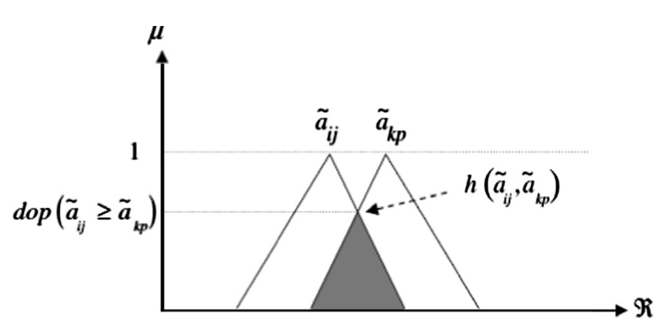


Fig. 2. Inconsistencies with triangular fuzzy numbers (Çakır [42]).

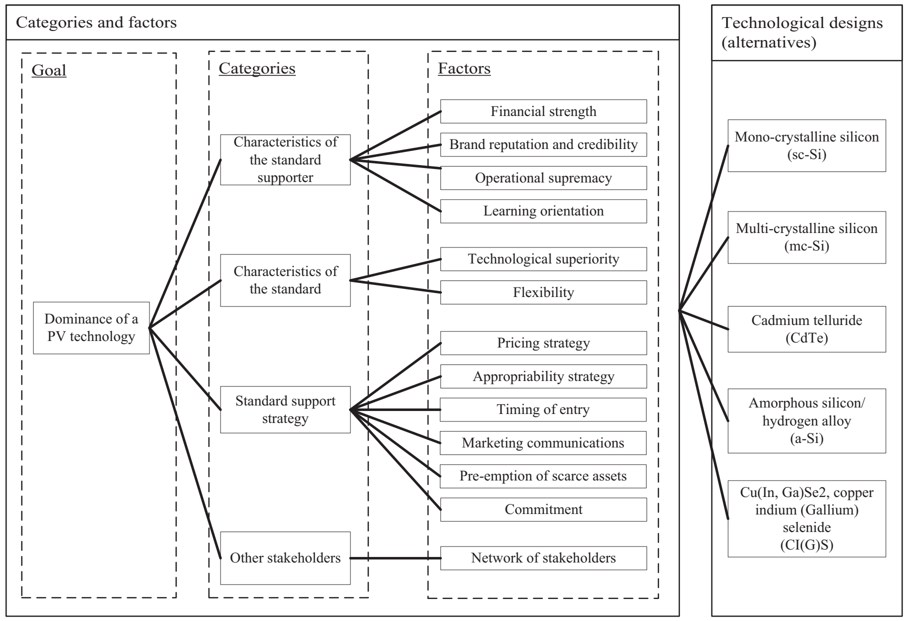


Fig. 3. AHP decision hierarchy.

Table 2
Results of crisp AHP Part I; Influence of factors.

Factors	Effect*	Local weight	Global weight	Ranking #
Characteristics of the standard supporter			*0.19*	*3*
Financial strength of the agent	+	0.16	0.03	12
Brand reputation and credibility	+	0.41	0.08	4
Operational supremacy	+	0.22	0.04	8
Learning orientation of the agent	+	0.22	0.04	9
Characteristics of the standard			*0.29*	*2*
Technological superiority	+	0.75	0.22	1
Flexibility	+	0.25	0.07	5
Standard support strategy			*0.46*	*1*
Pricing strategy	−	0.41	0.19	2
Appropriability strategy	−	0.05	0.02	13
Timing of entry	∩	0.24	0.11	3
Marketing communications	+	0.13	0.06	6
Pre-emption of scarce assets	+	0.08	0.04	10
Commitment	+	0.09	0.04	11
Other stakeholders				*4*
Diversity of the network	+	1	0.06	7

* Explanation of the symbols; + is positive influence on standard dominance, − is negative influence on standard dominance and ∩ means an inverted U shaped relation with standard dominance exists.

Table 3
Results of crisp AHP Part II; Status of technologies in relation to factors (local weights).

Factors	Technological design				
	sc-Si	mc-Si	CI(G)S	CdTe	a-Si
Characteristics of the standard supporter					
Financial strength of the agent	39.7%	39.7%	6.4%	10.6%	3.5%
Brand reputation and credibility	34.2%	34.2%	13.0%	13.0%	5.6%
Operational supremacy	47.7%	31.4%	4.9%	4.9%	11.1%
Learning orientation of the agent	33.3%	33.3%	11.1%	11.1%	11.1%
Characteristics of the standard					
Technological superiority	–	–	–	–	–
Flexibility	35.7%	35.7%	2.9%	16.2%	9.6%
Standard support strategy					
Pricing strategy	–	–	–	–	–
Appropriability strategy	35.3%	35.3%	5.4%	8.7%	15.2%
Timing of entry	36.0%	36.0%	3.0%	16.5%	8.6%
Marketing communications	20.0%	20.0%	20.0%	20.0%	20.0%
Pre-emption of scarce assets	39.3%	39.3%	3.3%	6.2%	12.0%
Commitment	20.0%	20.0%	20.0%	20.0%	20.0%
Other stakeholders					
Diversity of the network	36.7%	36.7%	4.6%	4.6%	17.3%

developments, and one expert from an installation company of PV panels for insights in consumer and other demand side needs.

Fig. 3 shows the list of factors that influence the technology selection process in a hierarchical structure using categories derived from the literature. We use tangible data to prioritize the underlying criteria for the factors *pricing strategy* and *technological superiority*. We use data on the current average market price of modules following a particular design in the largest PV market (Germany) for pricing strategy and data on the current average commercial efficiency of PV panels for technological superiority (this information is available upon request). Consequently, there is no need to rank the criteria of these two factors by use of the questionnaire, which also rules out the possibility of any consistency errors in the later (fuzzy-) AHP analysis.

Based on the structure in Fig. 3, we made a questionnaire consisting of two parts. Part I measures the importance of the categories in relation to the overlapping goal followed by the assessment of the importance of the factors. Part II measures the current status of the technological alternatives. Three experts from PV companies filled out Part 1 of the AHP questionnaire and three experts from research institutes filled out Part II. We approached different respondents for each part, since respondents from companies tend to favor their own technology and consequently may not deliver useful results in Part II of the questionnaire.

We analyzed the results from the questionnaire using both the crisp AHP from Saaty [27] and the logarithmic fuzzy preference programming (LFPP) method from Wang and Chin [37]. We checked the consistency of answers using the consistency ratio (CR) as proposed by Saaty [27] in the crisp AHP data analysis, and calculated the values λ^* and δ^* of each comparison matrix in the LFPP. If the answers in this questionnaire were found to be inconsistent according to the CR, we contacted the respondents and asked them to explain their ranking of the factor again after which we changed the ratings accordingly.

Table 4
Results of crisp AHP; Part I and II Combined (global weights).

Factors	Technological design					Ranking #
	sc-Si	mc-Si	CI(G)S	CdTe	a-Si	
Characteristics of the standard supporter						
Financial strength of the agent	0.013	0.010	0.002	0.002	0.002	12
Brand reputation and credibility	0.030	0.025	0.008	0.009	0.004	4
Operational supremacy	0.015	0.014	0.002	0.007	0.003	8
Learning orientation of the agent	0.017	0.012	0.003	0.004	0.005	10
Characteristics of the standard						
Technological superiority	0.063	0.052	0.041	0.037	0.028	1
Flexibility	0.023	0.027	0.006	0.008	0.008	5
Standard support strategy						
Pricing strategy	0.034	0.034	0.041	0.040	0.042	2
Appropriability strategy	0.008	0.011	0.002	0.002	0.002	13
Timing of entry	0.038	0.029	0.016	0.020	0.005	3
Marketing communications	0.019	0.017	0.010	0.009	0.006	6
Pre-emption of scarce assets	0.010	0.011	0.003	0.002	0.010	11
Commitment	0.013	0.011	0.006	0.006	0.005	9
Other stakeholders						
Diversity of the network	0.022	0.018	0.005	0.003	0.011	7
Total:	0.30	0.27	0.15	0.15	0.13	

Table 5
Results of LFPP Part I; Influence of factors.

Factors	Effect*	Local weight	Global weight	Ranking #
Characteristics of the standard supporter			*0.18*	*3*
Financial strength of the agent	+	0.15	0.03	13
Brand reputation and credibility	+	0.40	0.07	4
Operational supremacy	+	0.23	0.04	11
Learning orientation of the agent	+	0.23	0.04	10
Characteristics of the standard			*0.28*	*2*
Technological superiority	+	0.75	0.21	1
Flexibility	+	0.25	0.07	5
Standard support strategy			*0.48*	*1*
Pricing strategy	–	0.40	0.19	2
Appropriability strategy	–	0.06	0.03	12
Timing of entry	∩	0.21	0.10	3
Marketing communications	+	0.09	0.04	9
Pre-emption of scarce assets	+	0.11	0.05	8
Commitment	+	0.13	0.06	6
Other stakeholders				*4*
Diversity of the network	+	1	0.06	7

* Explanation of the symbols; + is positive influence on standard dominance, – is negative influence on standard dominance and ∩ means an inverted U shaped relation with standard dominance exists.

Table 6
Results of LFPP Part II; Status of technologies in relation to factors.

Factors	Technological design				
	sc-Si	mc-Si	CI(G)S	CdTe	a-Si
Characteristics of the standard supporter					
Financial strength of the agent	0.44	0.36	0.05	0.09	0.06
Brand reputation and credibility	0.39	0.33	0.11	0.13	0.05
Operational supremacy	0.36	0.35	0.05	0.17	0.07
Learning orientation of the agent	0.41	0.32	0.07	0.08	0.12
Characteristics of the standard					
Technological superiority	–	–	–	–	–
Flexibility	0.32	0.35	0.09	0.12	0.13
Standard support strategy					
Pricing strategy	–	–	–	–	–
Appropriability strategy	0.30	0.48	0.06	0.07	0.09
Timing of entry	0.29	0.26	0.18	0.21	0.05
Marketing communications	0.31	0.27	0.17	0.15	0.10
Pre-emption of scarce assets	0.29	0.31	0.07	0.06	0.28
Commitment	0.32	0.24	0.15	0.15	0.13
Other stakeholders					
Diversity of the network	0.37	0.32	0.07	0.04	0.20

5. Results

Tables 2 and 3 show the results using the crisp AHP analysis. For Part I and II of the questionnaire, and Table 4 shows the combined results. The results using the LFPP analysis are shown in Tables 5–7. The matrices in Part I are consistent since $\lambda^* > 0$, though 12 of the 33 matrices in Part II have values of $\lambda^* = 0$ and have an average value of $\delta^* = 0.55$ in the range between 0.05 and 0.93. The reason for these ratings can be mainly explained by the overlap caused by using triangular fuzzy numbers. Another reason may be the rank reversal problem introduced from using an AHP questionnaire.

The results from the crisp AHP and LFPP method (Tables 4 and 7) do not show much difference. In Part I, the first three factors have significantly higher ratings and their ranking is similar using both methods, although there are differences in the ranking starting from number 6. The data from Part II of the questionnaire only show a marginal difference in the total rating of a-Si but not enough to affect the order of technologies.

The results show that the standard support strategy is the most important category and that pricing strategy is a very influential factor in the dominance process. In the PV market, the prices per kW h of electricity produced are high compared to other electricity generating technologies (such as power stations fired by natural gas or coal) [43] which increases the payback time considerably.[5] If the payback time is too long, users will not adopt the PV technology [44]. Furthermore, currently competition on the international PV market is fierce [23,43] and developers are reducing their prices as much as possible. Some sellers are even willing to temporarily price below cost [43]. Such penetration pricing leads to a high installed base and thus to standard dominance [45].

Technological superiority has the highest ranking and is therefore the most influential factor in the dominance process. Since efficiencies of PV technologies are lower than those of other electricity generating technologies, an important driver for R&D besides cost reduction is efficiency increase [46]. Efficiencies have

[5] However, many countries have implemented policy measures (e.g., subsidies, Feed-in-Tariffs (FiT)) to make buying PV panels more attractive.

Table 7
Results of LFPP; Part I and II combined.

Factors	Technological design					#
	sc-Si	mc-Si	CI(G)S	CdTe	a-Si	
Characteristics of the standard supporter						
Financial strength of the agent	0.012	0.009	0.001	0.002	0.002	13
Brand reputation and credibility	0.027	0.023	0.007	0.009	0.004	4
Operational supremacy	0.014	0.014	0.002	0.007	0.003	11
Learning orientation of the agent	0.016	0.013	0.003	0.003	0.005	10
Characteristics of the standard						
Technological superiority	0.061	0.050	0.040	0.036	0.027	1
Flexibility	0.022	0.024	0.006	0.008	0.009	5
Standard support strategy						
Pricing strategy	0.034	0.034	0.041	0.041	0.042	2
Appropriability strategy	0.008	0.013	0.002	0.002	0.003	12
Timing of entry	0.029	0.026	0.019	0.022	0.006	3
Marketing communications	0.014	0.012	0.008	0.006	0.004	9
Pre-emption of scarce assets	0.015	0.016	0.004	0.003	0.014	8
Commitment	0.020	0.015	0.010	0.010	0.008	6
Other stakeholders						
Diversity of the network	0.022	0.018	0.004	0.002	0.012	7
Total:	0.30	0.27	0.15	0.15	0.14	

steadily increased during the last decades. Typical conversion efficiencies of first generation technologies are higher than those of second generation technologies (currently 15% to 20% compared to 7% to 15%) [22]. The most important reason why technological superiority is so important is that it relates to the payback time. The higher the efficiency of a PV panel is, the sooner investment can be recouped by selling electricity back to the grid or by having a 'free' source of electricity.

The results show that appropriability strategy is one of least influential factors in the dominance process. Since most patents issued in the PV industry only describe a minor part of a technology or production process [47], it is easy for companies to make variations on the patented technology and thus to work around the original patent. Financial strength is also a less important factor. This is because many governments subsidize PV development and deployment [22,48]. These subsidies directly affect financial resources that are available for PV development.

The results of the comparison of technologies in Part II of the questionnaire shows that sc-Si (first generation, mono-crystalline PV) has the best chances of becoming the dominant technology. The high rating of the first generation technologies is best explained by the relatively high efficiencies (technological superiority) in combination with relatively low prices, sometimes even below cost (pricing strategy). These technologies have been on the market longer than second generation technologies, which gives them a higher installed base which is an important factor for achieving dominance (timing of entry). Moreover, the production techniques for first generation technologies are based on those in the microelectronics industry which are proven techniques that have received considerable investments [49]. Therefore, it is relatively easy for manufacturers to start a production line for first generation PV technologies, since it is based on a well-known process.

6. Conclusion and discussion

This article is based on frameworks from existing literature, observations in the PV industry, and interviews with industry experts from PV manufactures, research institutes, universities and solar panel installation companies. We analyzed thirteen factors for standard dominance and five technological designs using the crisp AHP and the LFPP method. Our results show that pricing strategy and technological superiority are the most influential factors in the dominance process, whereas appropriability strategy and financial strength are the least influential. We found that sc-Si has the best chances of becoming the dominant PV technology.

This research contributes to the literature in several ways. First, by determining factors for standard dominance for PV technologies and assessing their weights, this research contributes to existing literature on dominant designs and standards [2–5]. According to Arthur [7], the path of a technology is often characterized by "nonergodicity" meaning that random idiosyncratic events (chance events) determine the outcome of a standards battle. It has been argued that these events are in fact precursors of other factors [3,4] and thus although these events could have powerful effects, they influence the likelihood that a standard achieves market acceptance (dominance) in an ordered way [2,3]. We contribute to the latter view and provide empirical proof for the belief that the result of standards battles is not entirely characterized by the existence of path dependencies but that standard dominance factors can be determined and that these factors can be assigned weights. This is the first time that actual weights for factors for standard dominance for PV technologies are established. We show that it is possible to model the process of standard selection for PV technologies. Second, to our knowledge, both the crisp AHP and the LFPP methods have never been applied in the area of selection of sponsored compatibility standards for PV technologies. This is the first time that both methods are applied for a standardization problem for PV technologies. Third, this research serves as a structured evaluation process for PV technologies. According to Rezaei et al. [50], using both the crisp AHP and the LFPP methods can validate the new LFPP method. The results of both methods, in a real-world case, are very similar, which shows the validity of LFPP.

A recommendation for further research is to study additional standards battles that are being vied for other electricity production systems (such as small wind mills or micro CHPs) and other energy related systems such as home automation and smart meters. By doing so, the generalizability of our findings can be explored. Furthermore, we suggest applying other MCDM methods such as (fuzzy) TOPSIS and (fuzzy) ANP to further validate the proposed approach in this paper. Also, the results of those methodologies can be compared with the result of this paper in order to better understand which method performs well under which conditions.

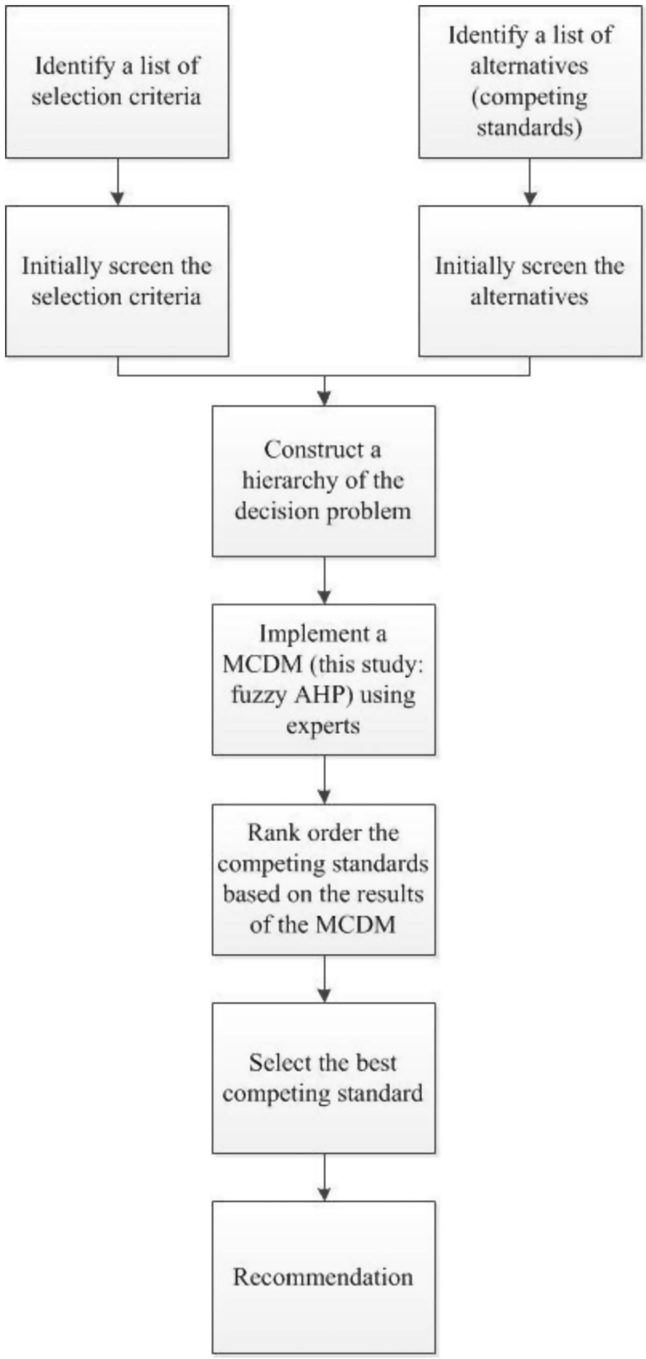


Fig. 4. A step by step approach that may be applied by practitioners that have to make the decision as to which standard should be supported.

The results of this study are useful for multiple stakeholders (e.g. energy policy makers and PV module companies) who have to make the decision as to which standard should be supported for PV technology. They can learn more about which factors are important and decrease uncertainty about their investments in standardization. A full step by step approach that may be applied by practitioners is presented in the flowchart in Fig. 4. To apply the proposed method correctly, the practitioner can interview a group of experts within its institution and differences in judgments should be discussed with the objective of reaching one overall judgment for each comparison in pairs. This exercise as such will increase the practitioner's understanding of the standards battle and it will provide them with a first indication as to which standard will have the best chances of achieving dominance (in the case of PV: sc-Si). Moreover, as far as they are in the position to influence certain factors, they can better see if a change in a factor may tip the balance in their favor or if it makes no sense to do further investments – because the victory is almost sure or because there is little chance to avoid loss of the standard.

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